A COMPUTATION GUIDE FOR TRAVELING-WAVE TUBE HELICIES

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by

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PREFACE

The background material for this guide was obtained while working at the laboratory of the Sylvania Electric Company, 500 Evelyn Avenue, Mountain View, California, during the third term industrial tour period from January 4 to March 19, 1954. This company has recently moved the traveling-wave tube program from its east coast laboratories to the newly established laboratory at Mountain View. Most of the personnel engaged in the program had little practical experience in the design of this class of tube and it is felt that a guide of this type would have been invaluable to them during the initial phases of traveling-wave tube development.

The writer would like to express his appreciation to Mr. P. G. Bohlke of the Sylvania Electric Company for his guidance in obtaining the background material and to Professors A. Sheingold, W. M. Bauer, and P. E. Cooper for their guidance in the preparation of this report.

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LIST OF SYMBOLS

a	-mean helix radius
f	-frequency
f	-figure 8 only, impedance reduction factor due to beam loading
k	-see equation 9
l	-length of wound helix
p	-helix pitch
r_1	-external radius of helix
r_2	-internal radius of helix
r_3	-external radius of electron beam
r_4	-internal radius of hollow electron beam
w	-width of helix conductor
ve	-electron beam velocity

A	-initial loss in setting up a traveling wave
B	-a function of space charge and helix attenuation
C	-gain parameter, defined by equation (14)
F	$-F_1 \times F_2$
F_1	-impedance reduction factor due to dielectric
F_2	-impedance reduction factor due to spatial harmonics
G	-gain of traveling-wave tube
I_o	-electron beam current
K	-helix impedance
L	-cold loss in db
N	-Number of active wavelengths of the helix
V_o	-electron beam voltage
α	-a constant
β_o	-free space wave velocity $= \frac{2\pi}{\lambda} = \frac{\omega}{c}$
β	-axial wave velocity $= \frac{2\pi}{\lambda_g} = \frac{\omega}{v}$
η	$-(\beta^2 - \beta_o^2)^{\frac{1}{2}} a$
λ	-free space wavelength
λ_g	-wavelength along axis of tube
ψ	-pitch angle of the helix, $\cot\psi = \frac{2\pi a}{p}$

SUMMARY

The traveling-wave tube is now coming of age and is expected to play a very important part in future electronics equipment. Much has been written about the theory of operation of the tube and the characteristics of several experimental tubes has been reported upon. Pierce (3)* has a very good bibliography in the back of his text. In addition the Electronics Research Laboratory of Stanford University has published many reports on the subject. These reports are the result of their work on traveling-wave tubes under a joint Army, Navy, and Air Force contract.

It is the purpose of this paper to outline a practical design precedure for one type of traveling-wave tube. There are several types of structures which will support a traveling wave. These structures include folded lines, loaded wave-guides and helicies. The last of these, the helix, is the structure which will be considered here.

A flow chart of design procedure, figure (1), will show the steps to be taken in order to arrive at a successful tube design. The solid lines indicate the progressive steps in the design. Dotted lines are used to indicate that a value, which exceeds the limits, has its dependence upon a previously established value. This previously established value will then have to be changed in order to bring the subsequent quantity within limits.

The values given for some of the parameters such as helix radius, a, and helix pitch, p will differ from the theoretical optimum values as given in Pierce (3). This difference can usually be justified,

*Numbers in parentheses refer to bibliography

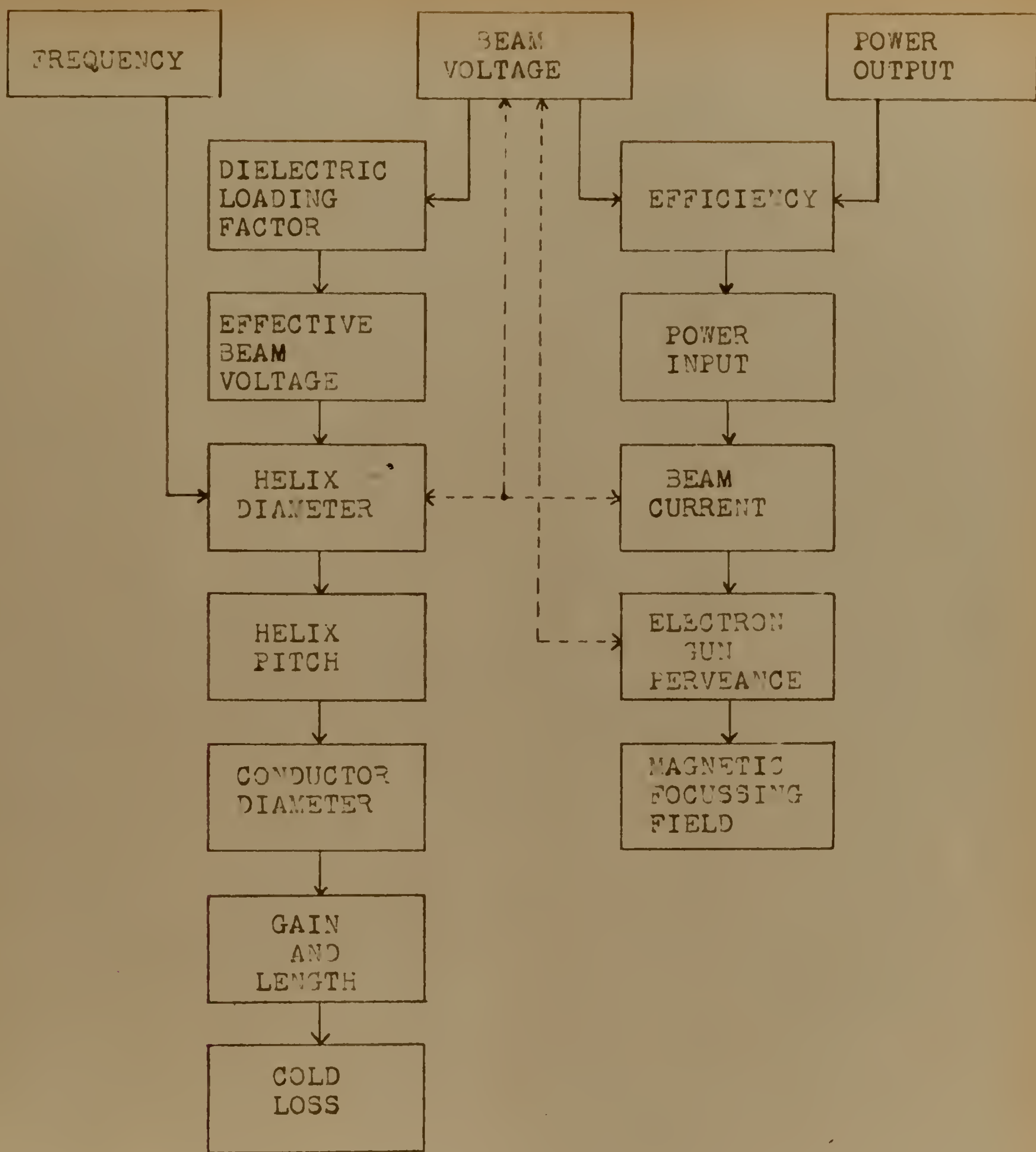


Figure 1

Flow chart of traveling-wave tube design procedure

qualitatively at least, as the result of later work. Notable is the work of Tien(5) on the evaluation of the helix impedance, K, in the presence of dielectrics and the work of Mathers and Kino(1) on the effect of an external shield upon the operation of the traveling-wave tube.

CHAPTER I

DESIGN LIMITATIONS

The design procedure to follow is valid only for low power traveling-wave tubes operating in the frequency range of about 2.0 to 8.0 kmc. A low power tube is defined as one whose average power output is 2 watts or less. The tubes are to be for general amplifier service and are not to be classed as low noise tubes. The same general procedure outlined here may be used for low noise design but there will be additional restrictions placed upon the choice of design parameters which are not presented here. Watkins (6), (7), has developed a procedure for the evaluation of the limiting parameters for low noise tubes. In general he restricts the power output to very low levels, 100 mw or less, by having a low perveance electron gun and an electron beam whose radius is small compared to the radius of the helix. Watkins has built experimental tubes using this method and has achieved results which support his theory very well.

The frequency limits are determined primarily by the physical size of the resulting tube. The tubes become very large at the low frequency end of the spectrum and very small at the high end. While small size is not in itself undesirable, the manufacturing tolerances become too small to be practical.

The power is limited by problems of heat dissipation and voltage breakdown which may require that values of the parameters for optimum gain characteristics be changed in order to produce an operating tube. The power output is limited by the efficiency of the tube and heat

dissipation in this range of operation rather than voltage breakdown. The efficiency of operation is low for the small tubes and will improve as the size, in terms of power, is increased.

CHAPTER II

THE QUANTITIES TO BE EVALUATED

1. The Helix.

The physical dimensions of the helix will have to be determined. The figure below will indicate the nature of the helix and the dimensions to be determined.

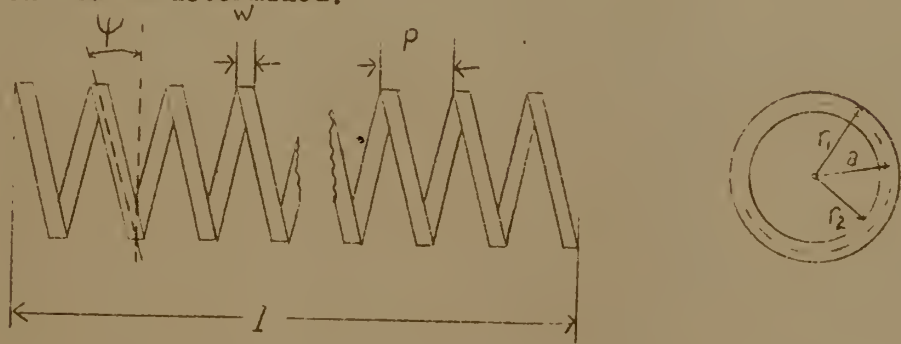


Figure 2

a	the mean radius to the center of the conductor
l	length of the wound helix
p	the pitch of the helix
r_1	external radius of the helix
r_2	internal radius of the helix
w	width of the helix conductor
ψ	the pitch angle of the helix and is equal to

$$\text{Cot}\,\psi = \frac{2\pi a}{p} \qquad (1)$$

2. The electron beam potential and current.

The electron beam potential, V_0, is the voltage required to accelerate the electrons to a velocity that will be equal to the axial

phase velocity of the traveling wave. The beam velocity is given by

$$v_e = 5.9 \times 10^7 \sqrt{V_0} \quad \text{cm/sec} \tag{2}$$

In most practical tubes the angle ψ is small enough so that the approximation that $\tan\psi = \sin\psi$ is valid. If this approximation is made and the wave is assumed to travel along the helix conductor at the velocity of light, c, then we may say that the required condition for the axial phase velocity and the electron beam velocity to be in synchronisim is

$$v_e = c \sin\psi \tag{3}$$

The electron beam current, I_0, is a function of the power output, the efficiency and the perveance of the electron gun. The perveance of the electron gun is defined as

$$\text{perveance} = \frac{I_0}{V_0^{3/2}} \tag{4}$$

3. Tube operating characteristics.

The previously mentioned quantities and dimensions will determine the operating characteristics of the tube. These characteristics will include gain, bandwidth and efficiency. After the preliminary design has been made using the center frequency of operation for the calculation these characteristics will have to be evaluated over the operating range of the tube to check the design.

CHAPTER III

LIMITING PARAMETERS

1. Synopsis

In Chapter I we discussed the limits of validity for the design precedure to be developed in this paper. There are further limits to impose upon the selection of values for the various parameters. These limits will apply to the design of most any type of traveling-wave tube since they are not dependent upon the factors of power output or frequency for their limitations. These limiting parameters of electron gun perveance, electron beam current density and magnetic focussing field will be discussed and evaluated.

2. Electron gun perveance.

The perveance of the electron gun was defined by equation (4). It will be seen that the perveance is not a function of current density but a function of V_0 and I_0 the electron beam voltage and current. It is however a function of the ratio of the radius of the helix to the radius of the electron beam. Traveling wave tubes require a parallel-flow cylindrical beam for their operation. This parallel flow is obtained by placing the entire tube in a uniform axial magnetic field. The perveance is limited by the fact that as the current is increased the potential at the beam center drops below the value at the outer edge by an amount equal to

$$V = .01513 \frac{I_0}{V_0^{\frac{1}{2}}} \text{ volts} \qquad (5)$$

This potential difference increases to the point where the beam is

blocked due to space charge effects. If the external radius of the beam, r_3, is assumed to be equal to the internal radius of the helix, r_2, the limiting value of current is reached when

$$I_o = 32 \times 10^{-6} \, V_o \quad \text{amperes} \tag{6}$$

When the beam radius is smaller than the helix radius this limiting value is reached at lower values of current. Figure 3 is a plot of the maximum perveance possible for different values of the ratio of the helix radius to the beam radius for a solid beam. Figure 4 is a similar plot for a hollow beam. The presence of ions in the tube will produce ion focussing of the beam and may increase the maximum value as much as six times the value given in equation (6). In any practical tube it is impossible to eliminate all the ions so the maximum values of perveance may be used as design limits which can be practically achieved.

2. Emission current density.

The emission current density of the cathode is dependent upon the beam current and upon the cathode area and is independent of the beam voltage. Successful operation of a traveling-wave tube depends upon the beam being near the helix, thus in most designs the ratio of r_2/r_3 is kept as near to 1 as is practical. The radius of the helix will therefore be a determining factor in the current density. At low frequencies the helix radii are large and decrease as the frequency increases. The radius of the helix may be expressed as

$$a = \frac{\text{constant}}{f} \tag{7}$$

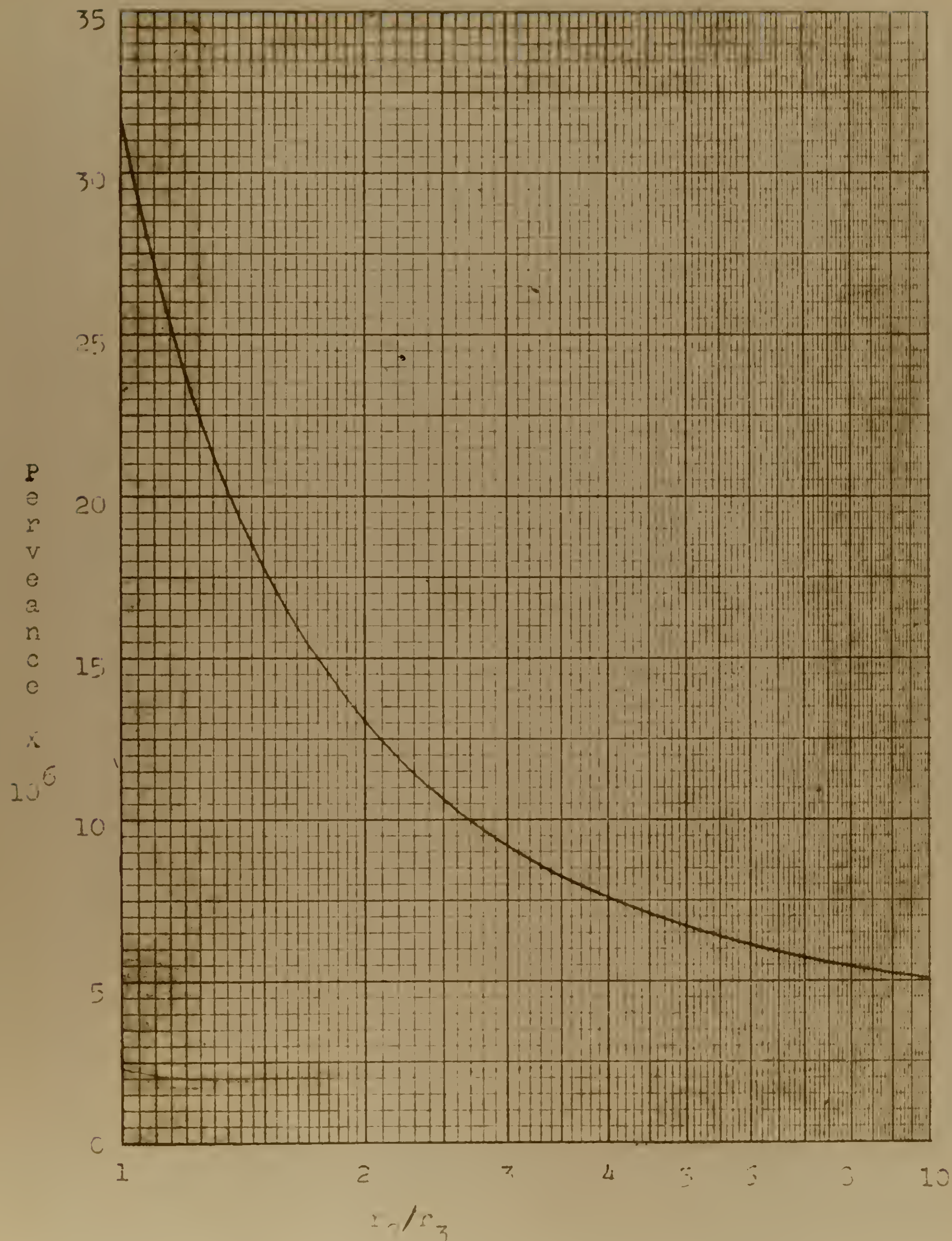
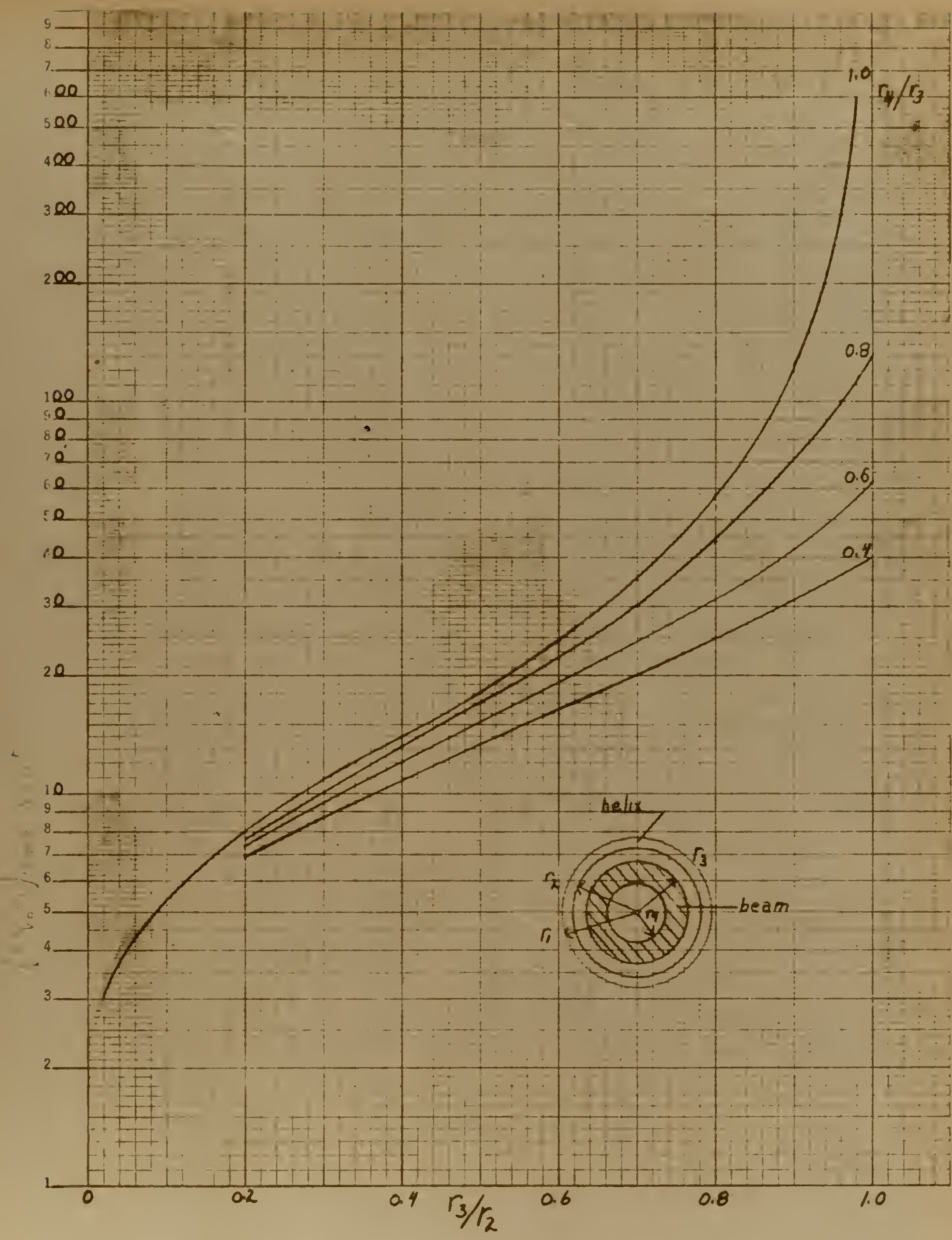


Figure 3

Maximum perveance of solid beam as a function of radius



r_4/r_3
1.0
0.8
0.6
0.4
helix
r_3
r_2
r_1
r_4
beam
r_3/r_2
0
0.2
0.4
0.6
0.8
1.0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
200
300
400
500
600

where the mean radius of the helix is a and the constant will be evaluated later. This indicates that the higher frequency tubes may be expected to be more critical with respect to current density than the low frequency tubes. In order to produce the parallel-flow beam required, a planar cathode with a radius equal to the beam radius is usually employed. Until recently the only practical planar cathodes were oxide coated cathodes. The emission current density of the oxide cathode is about 500ma/cm^2. There has been developed a new type of cathode material which is called the Phillip's cathode. These cathodes are formed from sintered tungsten impregnated with barium and strontium carbonates which are reduced to barium and strontium oxides when the tube is processed. These are indirectly heated cathodes which allow emission current densities several times that of the oxide cathode. The emission efficiencies are the same as those of the conventional indirectly heated oxide coated cathode.

3. Magnetic focussing field.

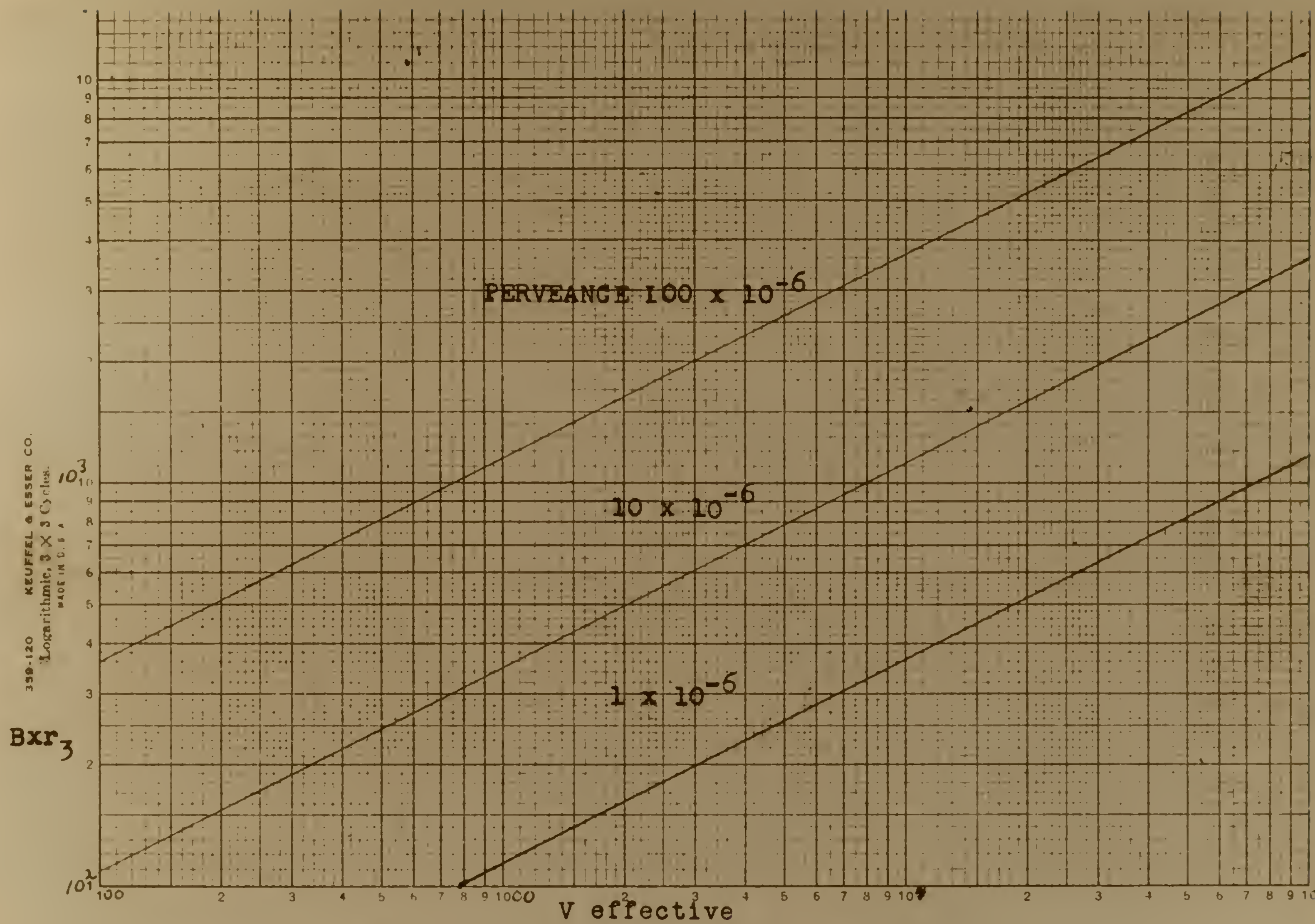
Pierce (4) has evaluated the magnetic field required to maintain the radius of the beam within specified limits. He gives the expression for the ratio of the maximum beam radius to the original beam radius as

$$\frac{6r}{r_3} = \left[(k^2 + 1)^{\frac{1}{2}} + k \right]^{\frac{1}{2}} \tag{8}$$

where k is defined as

$$k = \frac{I_o}{\sqrt{2}\,\pi\,\varepsilon\,\eta^{\frac{1}{2}} B^2 V^{\frac{1}{2}}\, r_3^2} = \frac{.34 V \times \text{perveance}}{B^2 r_3^2} \tag{9}$$

and B is the magnetic field in webers/meter^2, r is the maximum radius and r_3 is the original radius upon leaving the cathode. V is the effective beam potential which is approximately V_0 for low perveance guns or in the case where ion focussing takes place. Figure 5 is a plot of this equation with the perveance as a parameter when the maximum radius is to be 1.1 times the original radius. The magnets used for the focussing field are made of copper or aluminum wire wound solenoids and tend to become very heavy as the focussing field requirements increase. Towards this end it will be seen that it is very desirable to have a low voltage and low perveance electron gun in order to minimuze the weight.



Magnetic Field Required to Focus Beam ($r/r_3 = 1.1$)

Figure 5

CHAPTER IV

THE DIELECTRIC LOADING FACTOR

The dielectric loading factor is important in the design of traveling-wave tubes because it is a determining factor in achieving the synchronous velocity of the wave traveling along the helix to the velocity of the electron stream. If the axial phase velocity of the wave is measured with the helix in free space and compared to the axial phase velocity of the wave after the tube is mounted in the helix it will be found that the latter velocity is less. This reduction in phase velocity is due to the presence of the dielectric walls of the tube and is analogous to the reduction of the phase velocity in coaxial cables. Tien (5) has conducted an extensive investigation into the computation of the dielectric loading factor. In his analysis he has assumed an infinitely thin helical tape model where there are two media of different dielectric constants whose boundary is a cylinder of the same radius as that of the helix. He defines the dielectric constant as the ratio of the phase velocity of a helix in dielectric surroundings to the phase velocity of the same helix in free space. It may be computed from the ratio of the cotangents of the helix angle ψ as computed in free space and with dielectric surroundings. The first expression given below is the free space case and the second is the case with dielectric surroundings.

$$\cot \psi = \frac{n}{\beta_0 a} \left(\frac{I_0(n) K_0(n)}{I_1(n) K_1(n)} \right)^{\frac{1}{2}} \tag{10}$$

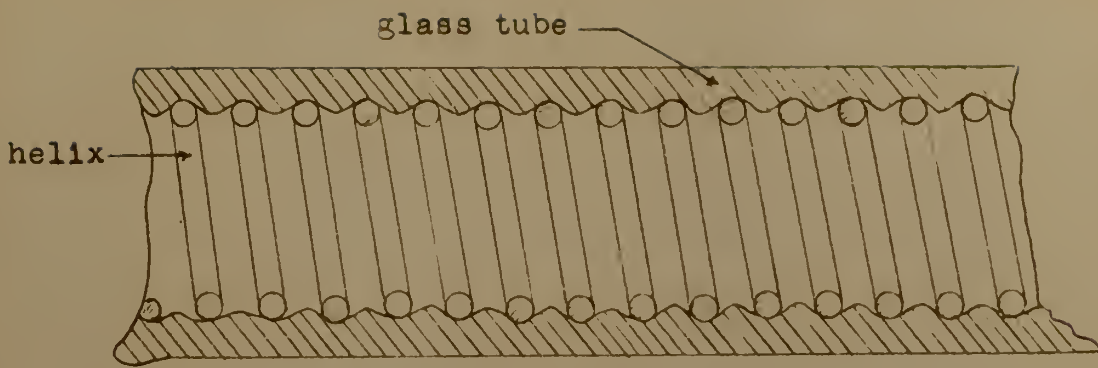
$$\operatorname{Cot} \psi = \left\{ \frac{ n^i \dfrac{I_0(n^i)}{I_1(n^i)} - n^e \dfrac{K_0(n^e)}{K_1(n^e)} }{ \dfrac{\beta_i^2 d^2}{n^i} \times \dfrac{I_1(n_i)}{I_0(n^i)} + \dfrac{\beta_e^2 d^2}{n_e} \times \dfrac{K_1(n_e)}{K_0(n_e)} } \right\}^{\frac{1}{2}} \qquad (11)$$

Where the I's and K's are modified Bessels' functions, the superscript e and i refer to the conditions external to the helix and internal to the helix respectively and $n^{i,e}$ is defined as

$$n^i = (\beta^2 - \beta_i^2)^{\frac{1}{2}} d \qquad n^e = (\beta^2 - \beta_e^2)^{\frac{1}{2}} d$$

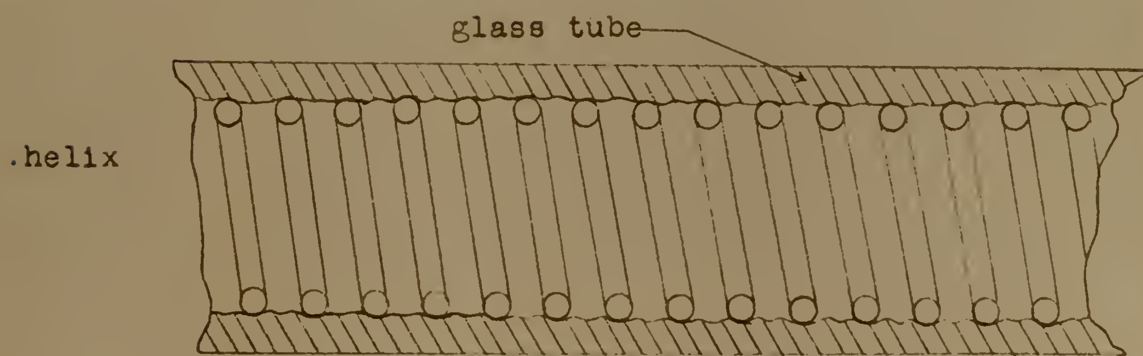
where $\quad \beta = \frac{2\pi}{\lambda} = \frac{\omega}{v}$

The actual computation of the dielectric loading factor is difficult due to the assumputions made in deriving equations (10) and (11). Practical helicies are usually quite thick for mechanical strength and it is difficult to get a sharp boundary between the dielectric wall of the tube and the interior. Three methods of mounting the helicies in the glass tube are shown in Figure 6 along with the average dielectric loading factor associated with them. In Figure 6a and 6b the helix is mounted on a precision mandrel and the wire and mandrel are inserted in the tube. The glass tube is then shrunk down around the helix after which the mandrel is removed. The difference between 6a and 6b is that in the method of 6b the space between turns of the helix is filled with a bifilar winding of copper wire prior to the shrinking process. The copper wire is removed after shrinking. This method will reduce the average proximity of



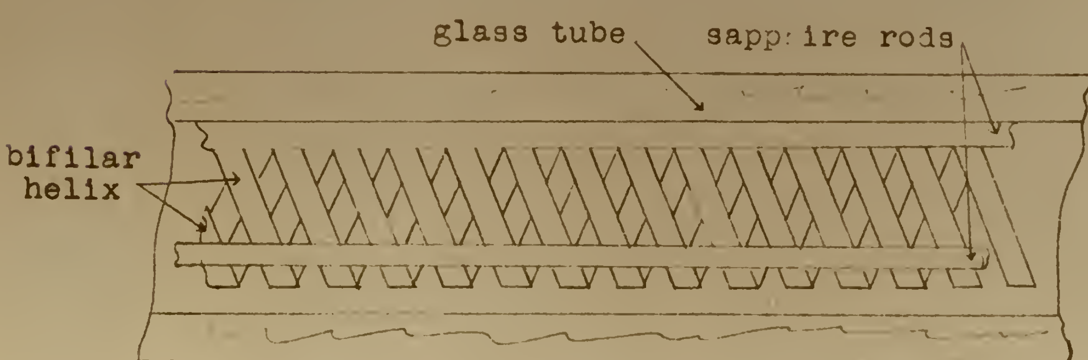
D.L.F. 0.68 to 0.72

a



D.L.F. 0.75 to 0.80

b



D.L.F. 0.85 to 0.95

c

Methods of mounting the helix

the glass and thus reduce the dielectric loading. It will be seen that the shape of the dielectric boundary would make accurate computation extremely difficult even if the shape of the boundary could be accurately expressed. In practice the phase velocity along the helix may be most easily found by measurement. This is done by having a probe which can be moved along cylindrical coordinates outside the helix or by a very small probe inside the helix. The former method is preferable since it will introduce less error in the readings due to having less influence on the fields set up by the wave on the helix.

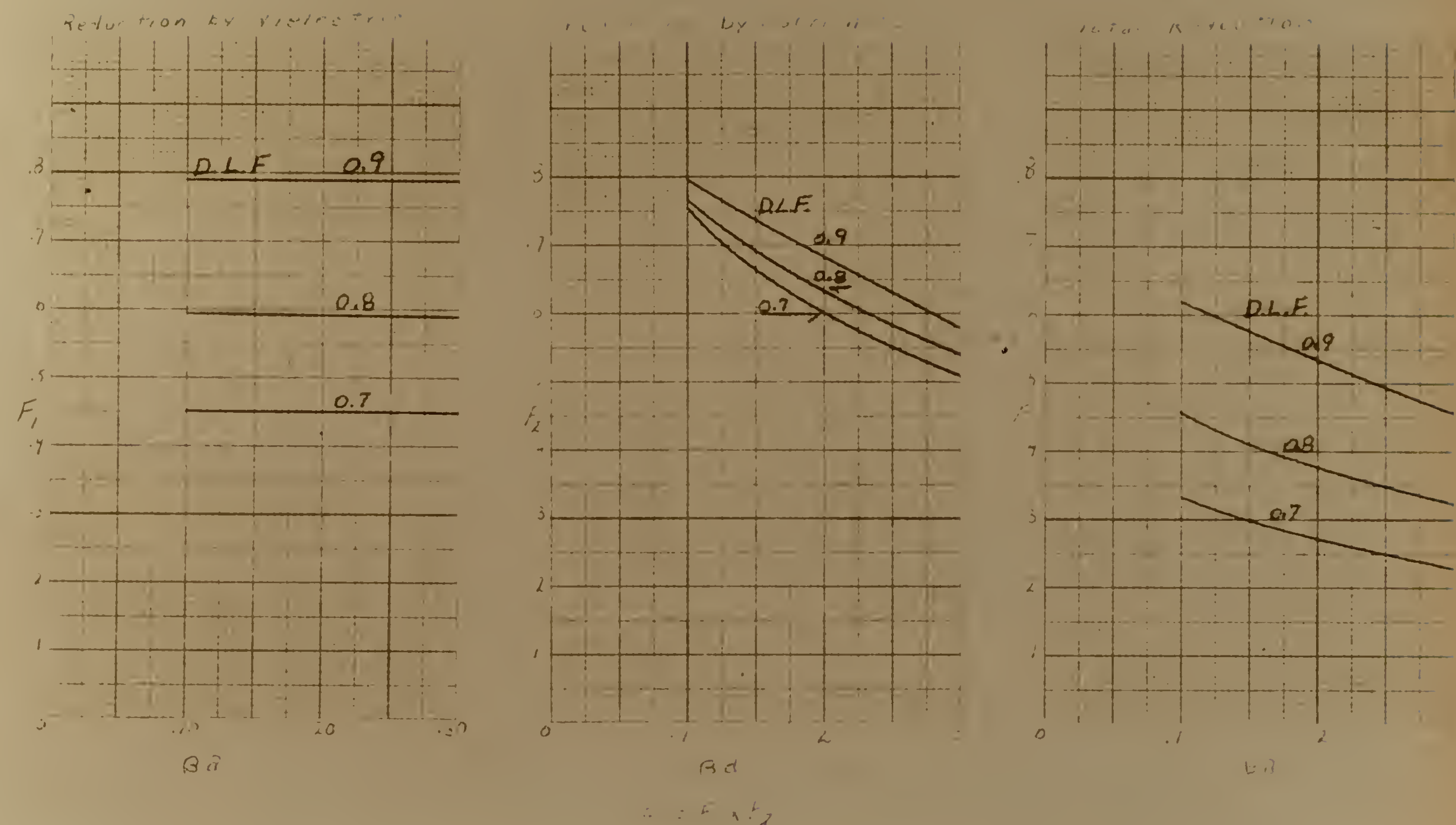
The dielectric loading factor has two effects upon the performance and design of the tube. The first effect is the reduction of the helix impedance, K, and the second is to make the effective V_0 used for computing the beam velocity higher by a factor of $1/(\mathrm{D.L.F.})^2$ where D.L.F. is the dielectric loading factor defined by equations (10) and (11). The latter effect will be discussed more fully when the geometry of the tube is computed.

The reduction in helix impedance as computed by Tien (5) is in very close agreement with the experimentally derived values. There was a factor of almost two between the previously derived value of impedance and the experimental value. The experimental value was less than the theoretical value. Previous derivations had been carried out by Pierce (3) and others using the case where the helix was in free space with no dielectric other than air near the helix. The helix impedance equation was given by Tien (5) as

$$K = \left\{ \frac{\omega \varepsilon d^4}{2\pi B^3 \eta} \left[\left(1 + \frac{I_0 K_1}{I_1 K_0} \right) \left(I_0^2 - I_0 I_2 \right) + \frac{I_0^2}{K_0^2} \left(1 + \frac{I_1 K_0}{I_0 K_1} \right) \left(K_0 K_2 - K_1^2 \right) \right] \right\}^{-1} \tag{12}$$

$I_0 = I_0(\eta) \cdot \cdot \cdot \cdot$

Once the dielectric loading factor has been determined the reduction in helix impedance due to it may be computed easily from values found on Figure 7 which has been taken from the report by Tien (5). F is the amount by which the free space impedance is reduced due to the presence of a dielectric and the presence of spatial harmonics.



D.L.F
0.9
0.8
0.7
F_1
F_2

CHAPTER V

GAIN OF THE TRAVELING-WAVE TUBE

1. The gain equation.

The equation for the gain of a traveling-wave tube is given by Pierce (3) as

$$G \quad A + (BCN - \alpha L) \tag{13}$$

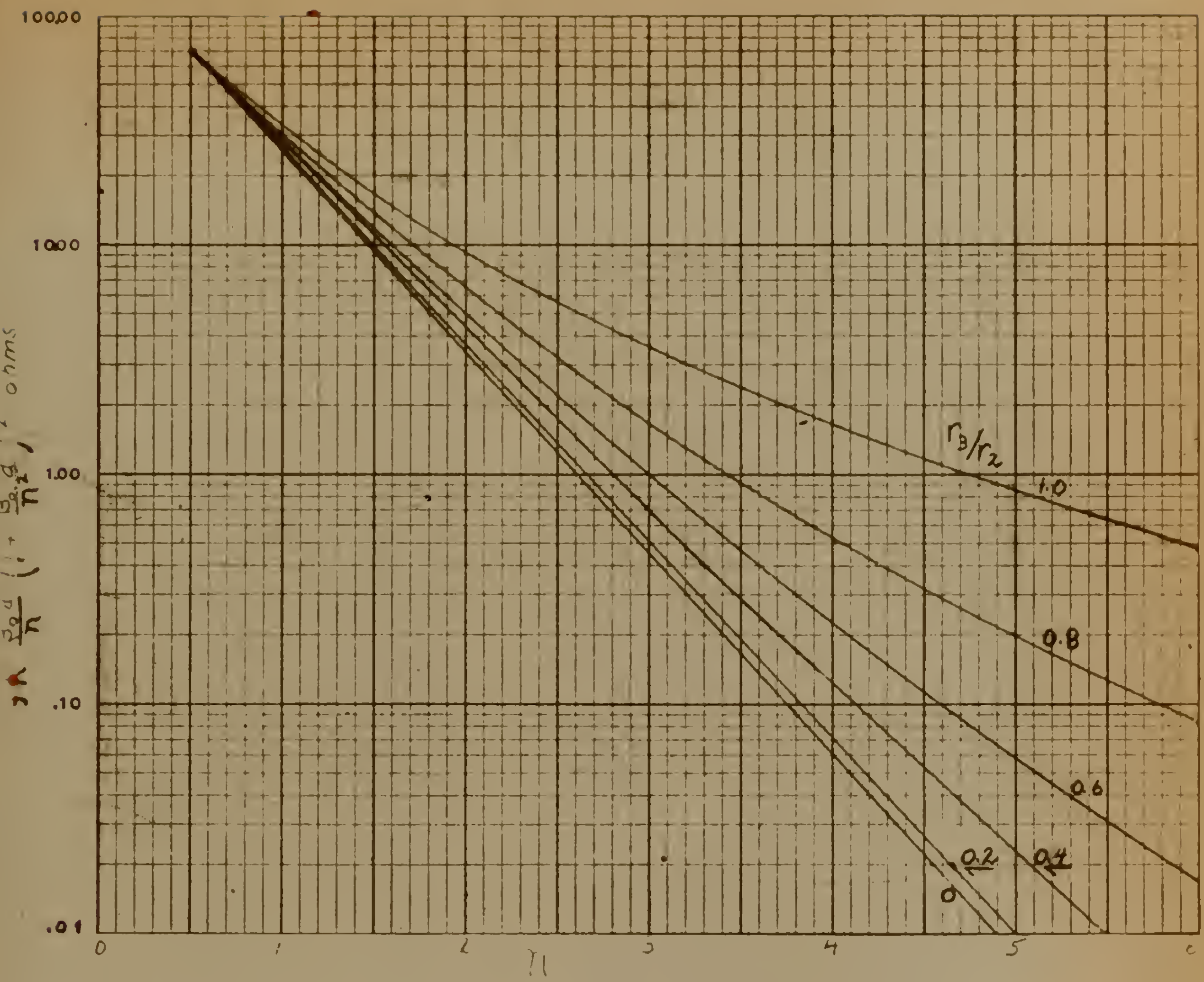
Where A represents the initial loss in setting up the increasing wave, B is a factor which depends upon the space charge in the tube and upon the helix attenuation, N is the number of active wave lengths of the helix and C is the gain parameter defined by

$$C^3 = K \frac{I_0}{4V_0} f \tag{14}$$

Where K is the helix impedance defined by equation (12), I_0 and V_0 are the beam current and voltage respectively and f is a factor dependent upon the ratio of beam diameter to helix diameter. L is the loss of the helix as measured without any electron beam and is called the cold loss. α is a constant whose value is always less than 1 and represents the fraction of the cold loss to be subtracted from the tube gain. The quantities A and B are relatively constant over the useful operating range of the tube. C and N will vary with frequency over the operating range in such a manner that the gain will remain essentially constant, thus giving the desired broadband characteristics of the traveling-wave tube.

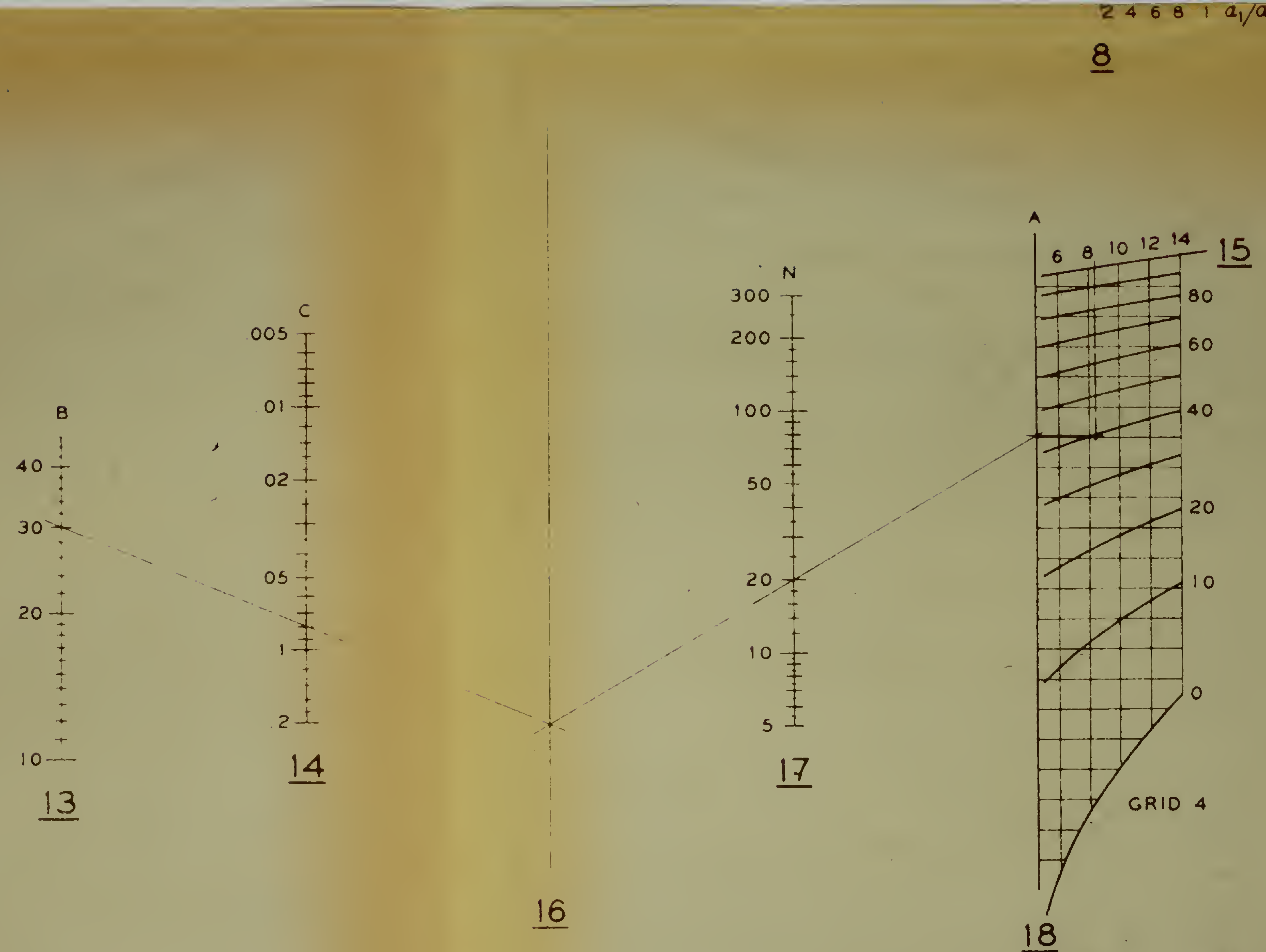
Previous to the report by Tien (5) the helix impedance was reduced by a factor of two in order to agree with the experimentally derived values when it was used for computing the gain of the tube. The most accurate evaluation of the helix impedance can be made by computing the helix impedance by means of equation (12) and applying the reduction factor by dielectric loading and spatial harmonics from Figure 7. Pierce (3) has evaluated the impedance reduction factor f and Figure 8 is his plot of f as a function of the ratio of the radius of the beam to the radius of the helix.

The foregoing is not sufficient to permit calculation of the gain of the tube. Appendix VII of Pierce (3) lists all the necessary information for the computation of the gain. To get an accurate estimate of the gain the modifying information on the value of K as done by Tien (5) should be included. The computations are relatively long and laborious and may be off by several decibels in the final form. As an example I computed the gain of a 2.0 to 4.0 kmc tube by the method outlined in Pierce (3) and using the modification of Tien (5). The gain was computed at every 100 mc from 1.9 kmc to 4.1 kmc. The time required was two working days to get a picture of the bandwidth of the tube. Bell Laboratories has developed a nomograph to compute the gain of the tube in a much shorter time. It will be noted that the ratio of ideal to actual circuit impedance is used. By using the relations developed by Tien (5) an accurate computation of gain may be made. The results of my previous work were checked using this nomograph. The time required was less than two hours to get a complete gain picture for the tube. The nomograph is included here as Figure 9.



100.00
10.00
1.00
.10
.01
0
1
2
4
5
r_3/r_2
1.0
0.8
0.6
0.4
0.2
0
ohms

Figure 9

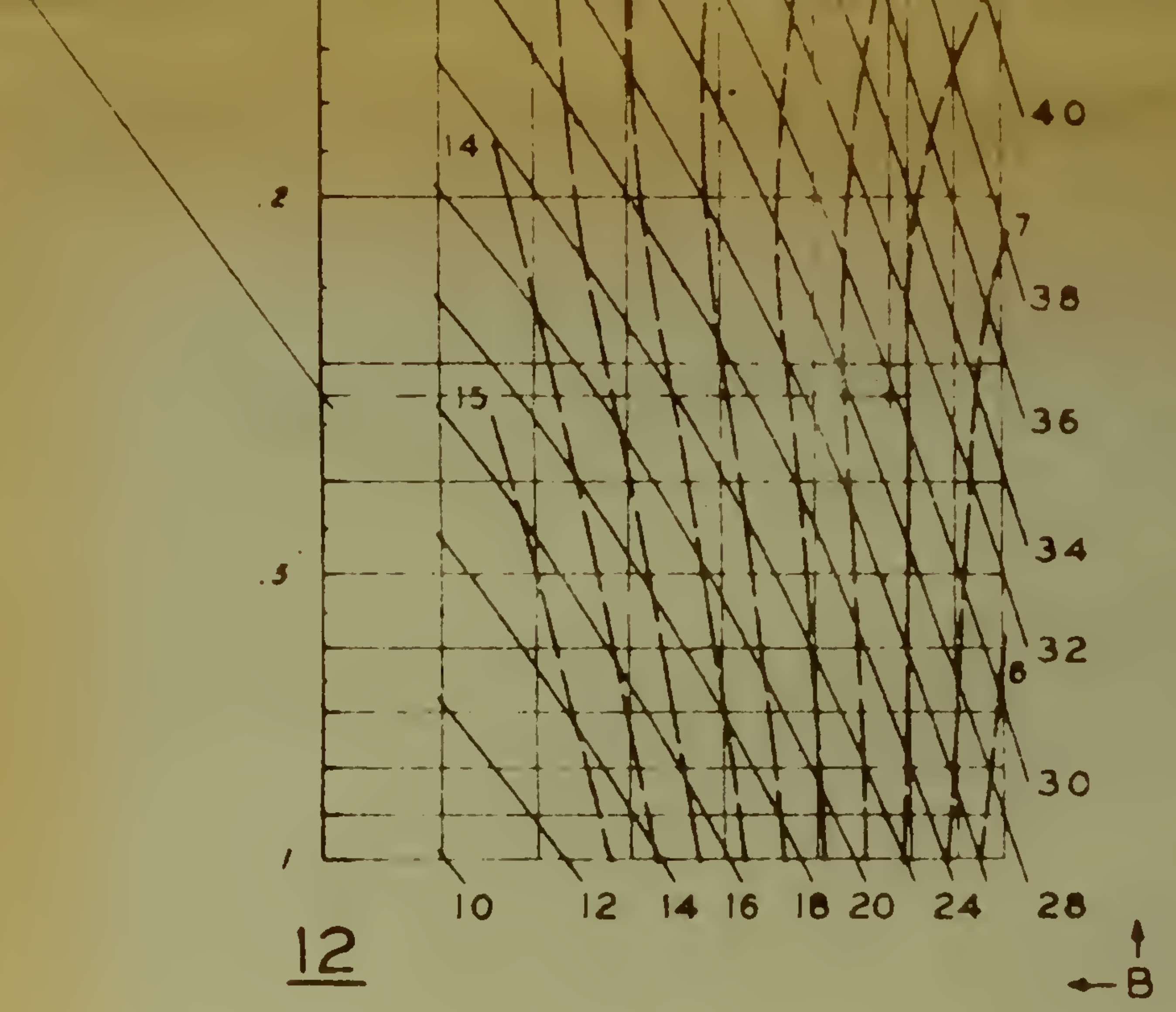


C C CUTLER
NOMOGRAPH OF TRAVELING WAVE RELATIONS

7

100

9



GRID 3

INSTRUCTIONS

1. SCALE VALUES OF TUBE CONSTANTS ON APPROPRIATE LINES AND GRIDS.
2. TRANSFER POINTS ON GRIDS 1 AND 2 HORIZONTALLY TO ASSOCIATED HEAVY LINES TO LEFT OF GRIDS.
3. CONNECT POINTS ON LINES 1 AND 2 AND EXTEND TO INTERSECT PIVOT LINE 3
4. CONNECT INTERSECTION ON 3 TO POINT ON 4 AND EXTEND TO INTERSECT 5.
5. CONNECT INTERSECTION ON 5 TO POINT 6 AND EXTEND TO 7
6. CONNECT POINTS ON 1 AND 8 AND EXTEND TO INTERSECT 9.
7. CONNECT INTERSECTIONS ON 7 AND 9 AND EXTEND TO INTERSECT 12.
8. DRAW LINE FROM 12 HORIZONTALLY INTERSECTING GRID 3.
9. CONNECT POINT ON 10 TO INTERSECTION ON 7 INTERSECTING 11.
10. DRAW LINE FROM INTERSECTION ON 11 PARALLELING ARRAY AND INTERSECTING GRID 3 VERTICALLY.
11. VALUES OF A AND B CAN BE READ FROM INTER SECTION OF CONSTRUCTION LINES ON GRID 3.
12. APPLY THESE VALUES OF A. B AND C TO LINES 15. 13 AND 14 RESPECTIVELY.
13. CONNECT POINTS ON 13 AND 14 AND EXTEND TO INTERSECT 16.
14. CONNECT INTERSECTION ON 16 TO POINT ON 17 AND EXTEND TO INTERSECT 18.
15. DRAW LINES HORIZONTALLY FROM INTERSECTION ON 18, VERTICALLY FROM POINT ON 15.
16. READ GAIN FROM INTERSECTION IN GRID 4.

DEFINITION OF TERMS

K_2/K_1 - RATIO OF ACTUAL TO IDEAL CIRCUIT IMPEDANCE

$a/\lambda g$ - CIRCUIT RADIUS MEASURED IN GUIDE WAVELENGTHS

a_1/a -- RATIO OF BEAM TO CIRCUIT RADII

V_0 --- BEAM VOLTAGE

I_0 ---- BEAM CURRENT IN MILLIAMPERES.

L ---- ATTENUATION db PER WAVELENGTH.

N ---- LENGTH OF TUBE IN WAVELENGTHS

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Three general conditions must be maintained in order to have the gain of the tube a maximum over the operating range.

1. The helix impedance should be high.
2. The phase velocity of the traveling wave must stay constant with respect to the electron beam velocity.
3. The excitation of modes other than the fundamental must be minimized.

The effect of dielectric loading upon the helix impedance has been previously discussed. In general as the dielectric loading increases the helix impedance decreases. This effect is most prominent at low frequencies. There is a secondary effect of dielectric loading which is most prominent at higher frequencies. The dielectric loading has the effect of maintaining synchronism between the wave and the beam which extends the high frequency gain of the tube. The proper choice of dielectric loading will permit the extension of the bandwidth of the tube at a slight sacrifice of power output due to the reduction of helix impedance.

The excitation of modes other than the fundamental has been examined by Tien (5) and he finds that it is one reason for the difference between the theoretical and experimental values of K. This reduction factor is plotted in Figure 6 as a function of dielectric loading factor, frequency and helix radius. Qualitatively we can say that the power loss due to spatial harmonics increases directly as the helix radius and the ratio of helix pitch to conductor width.

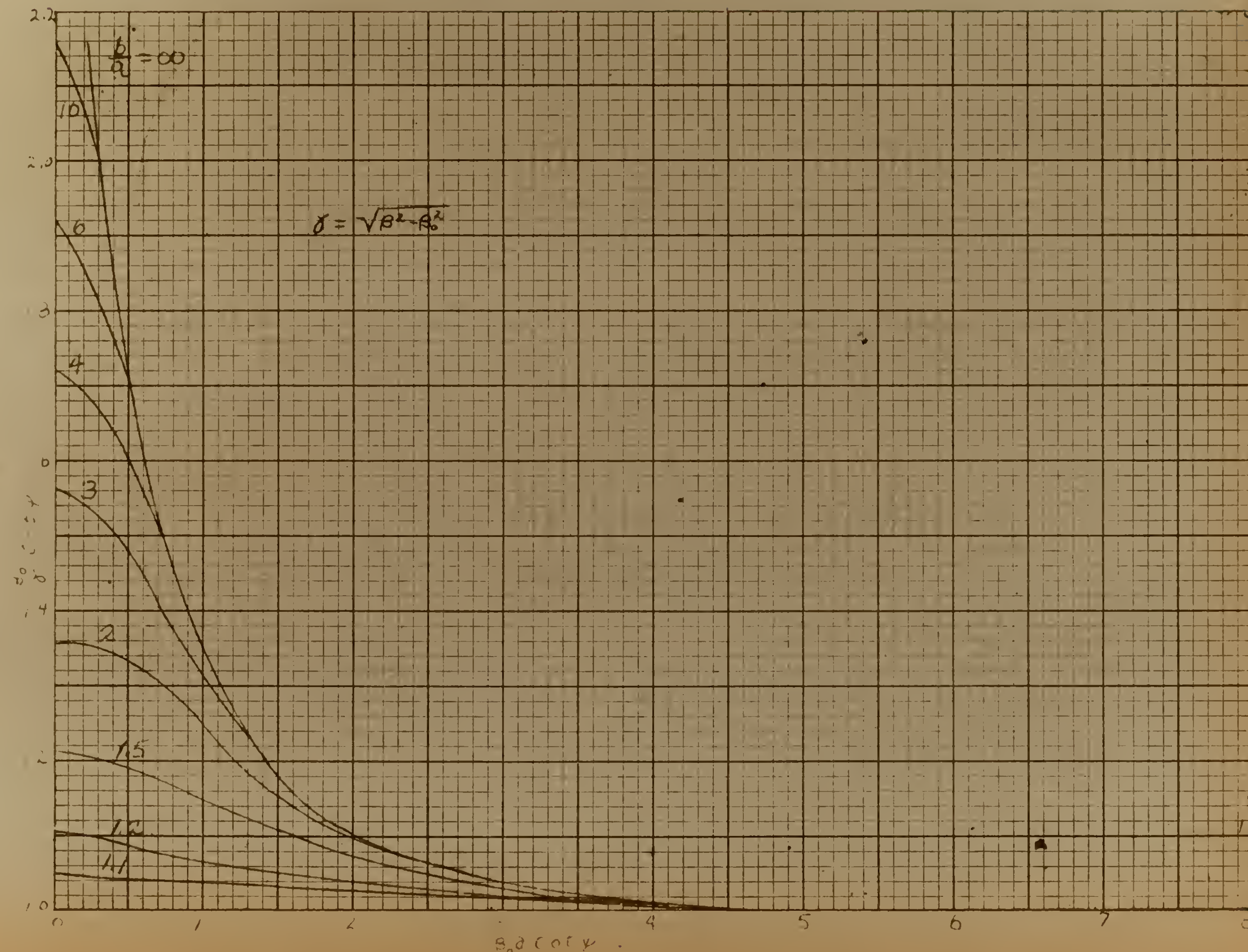
CHAPTER VI

COMPUTATION OF TUBE DIMENSIONS

1. Diameter.

The dispersion of a traveling-wave tube is defined as the variation of the phase velocity of the traveling wave as a function of frequency. In Figure 10 we have a dispersion curve plotted for the case when the helix is surrounded by a conducting shield, the abscissa is directly proportional to frequency but the ordinate is only approximately proportional to frequency. This curve was taken from the work of Mathers and Kino (1) who investigated the effects of an external shield and an internal conductor upon the operation of traveling-wave tubes. Their findings indicate that by the proper choice of shielding the bandwidth of the tube may be significantly extended without too large a sacrifice in gain and that the output impedance can be made to match that of the low impedance coaxial lines now in use.

It was previously mentioned that the diameter of the tube should be a minimum to have a high value of K. There is a limit to this minimum however, Figure 9 shows that if a low value of a is chosen the bandwidth of the tube will be limited since the electron beam velocity was fixed when V_0 was fixed. There must be a compromise value which will be an optimum. There is a range for β_0 a which are between 0.1 and 0.3 which will give a satisfactory tube. A value of 0.1 for $\beta_0 a$ at the center frequency is usually chosen. A further restriction is that the value of η lie in the range of from 1.0 to 2.5. If η is less than 1 the required velocity of the electron beam becomes excessive and if η is greater than 2.5 there is poor



$\frac{b}{a} = \infty$
10
6
4
3
2
1.5
1.2
1.1
$\gamma = \sqrt{\beta^2 - \beta_0^2}$
2.2
2.0
1.0
0
1
2
4
5
6
7

interaction between the traveling wave and the electron beam.

When the tube is operated at low voltages β_o is much less than β and we can say that $\eta \approx \beta$. If this is assumed we can then draw a simple relationship between $\beta_o a$ and η

$$\beta_o a = \eta \frac{v_p}{c} \tag{15}$$

where v_p is the effective axial phase velocity and is equal to

$$v_p = v_e / \text{ dielectric loading factor} \tag{16}$$

and

$$v_e = \text{ beam velocity} = 5.931 \times 10^7 \ (V_o)^{\frac{1}{2}} \text{ cm/sec} \tag{17}$$

Thus a rapid check may be made to insure that both restrictions are met simultaneously.

2. Pitch.

If we have a wave traveling along the helix with a velocity, v, its axial velocity will be $v \sin\psi$. This velocity, v_p, must be equal to the electron beam velocity, v_e, in order to synchronize properly. Equations (1), (16), and (17) may be manipulated algebraicly to yield the pitch, p.

$$p = \frac{2\pi a \sqrt{V} \times 1.977 \times 10^{-3}}{\left[(D.L.F)^2 - .66 \times 10^{6} V_o\right]^{\frac{1}{2}}} \text{ cm/turn} \tag{18}$$

If the angle ψ is small enough to assume that $\sin\psi = \tan\psi$ equation (18) may be simplified to

$$p = \frac{2\pi a \sqrt{V_o} \times 1\,977 \times 10^{-3}}{D.L.F} \tag{18a}$$

In both the previous equations the initial value of the velocity of the wave along the helix was assumed to be the free space wave velocity which is the velocity of light, c.

3. Conductor width.

The decision of whether to use a tape or wire for the conductor and the size of the conductor must now be made. In the ideal case an infinitely thin tape was assumed and this is the best shape to use but there are practical factors of tube construction which also influence the choice. First it is desired to limit the dielectric loading to a reasonable value. If the helix is to be in direct contact with the tube wall as shown in Figure 6a, a round conductor will reduce dielectric loading, whereas in the case of Figure 6c, a tape may be used because the mounting rods have only a slight effect on loading. The mechanical strength of the helix must also be considered when winding the helix. If the width is small a round conductor is better than a tape because of the configuration of the fields between the turns of the helix for thick conductors concentrates the field there. This does not leave much of an external field to interact with the electron beam. In practice a round wire is used for diameters up to .020 inches and tapes are used for conductor widths greater than this.

The width of the tape is usually expressed as a fraction of the helix pitch, p. If the ratio of width to pitch is too large, there will be a serious reduction in the field within the helix and low gain will result. Conversely if the ratio is too small there will be spatial harmonics present which will reduce K and consequently the

gain will be reduced. Tubes have been built using ratios from 1/5 to 3/4. The optimum value has been found to be 1/2, that is the width of the conductor is 1/2 the pitch. The helix is commonly wound of tungsten wire or tape. It must have a constant pitch which is free from any variation along the length of the helix. Discontinuities in pitch may cause reflections within the helix and these reflections will cause a reduction in gain. Tungsten has a very good dimensional stability when heated which makes it a desirable material to use for helicies.

4. Length of the helix.

The length of the helix governs the gain of the tube as may be seen from the gain equation. A nominal value for the length of the helix is 40 wavelengths at mid-frequency. The gain of the tube is computed using this value and then the length may be adjusted as necessary to give the desired gain.

5. Summary.

We have now established the geometry of the helix for a traveling-wave tube. Previously the direct current parameters were determined. From these two statements one might conclude that the design of these parts of the tube was complete. This would be an erroneous assumption. The properties of the tube such as gain, bandwidth and dispersion must be computed for the operating range of the tube. If the specifications cannot be met the design will have to be modified. There are many interrelated values which will have to be adjusted to produce the desired result. The so-called optimum values indicated here do provide a sound basis for the initial design.

CHAPTER VII

COLD LOSS

1. The necessity for cold loss.

The cold loss L was mentioned in connection with the gain equation. The cold loss is necessary to prevent any feedback in the helix which would cause the tube to oscillate. The theory of the traveling-wave tube indicates that in order to satisfy the boundary conditions there are four waves set up in the tube. They are a forward increasing wave, a forward attenuated wave, a backward increasing wave and a backward attenuated wave. The last of these is so small that it is usually neglected. The sum of the other three waves is the net wave present in the tube. If cold loss is not put in the tube the backward increasing wave might predominate under certain operating conditions. This would make the tube useless as an amplifier.

2. Methods of introducing cold loss.

A brief rule of thumb for cold loss is to have a cold loss approximately 10 decibels greater than the desired forward gain of the tube as computed without any loss. Owens (2) has given the value of cold loss as equal to 1/2 the net gain of the tube in decibels. The work which has been done at Stanford University indicates that this latter value is too low unless the output of the tube is very well matched.

Cold loss may be introduced in the tube in several ways: a resistive coating may be applied to the inner or outer surface of the tube, lossy ceramic collars may be placed on the helix, the conductor may be iron plated, or coupled helicies made of a resistance wire such

as Karma wire may be used. Owens (2) has investigated the later method in some detail and it appears very promising. The coupled helix method permits the cold loss adjustment to be made after the tube has been completed in all other respects.

The cold loss is generally concentrated in a short region nearer to the input end of the tube than the output end. A good approximation of the gain may be made by assuming the loss to be distributed over the entire length of the tube. More accurate results are obtained if the tube is treated in three parts, two of which have no attenuation and a third part with the entire cold loss evenly distributed along its length.

CHAPTER VIII

CONCLUSIONS

The final design of any device, electrical or mechanical, is usually the result of many compromises between the optimum values in order to meet the specifications of performance. The design procedure outlined in this report has been aimed at producing a tube with a maximum gain-bandwidth product. The gain of the tube is expected to be 30 db or more with a bandwidth factor of two to one or better. If higher gain is desired the bandwidth must be sacrificed and vice-versa. There have been many successful tubes built using the criteria set forth in this paper and there have been other good tubes built which deviated from these criteria in one or more respects. These deviations were necessary in order to meet certain specific requirements of performance.

The designer of the traveling-wave tube has one factor in his favor. Once the physical geometry of the tube has been determined, he may build a sample helix and subject it to a series of cold tests such as cold loss and phase velocity measurements. These tests will provide the necessary information to permit accurate computation of the gain characteristics of the tube without having to build an electron gun or evacuate the tube.

In conclusion, I would like to say that the traveling-wave tube is about to emerge from the laboratory and become a useful device in the field of electronics. There are still some disadvantages such as heavy magnets for focussing, low efficiency and the need for high current power supplies for the magnet. Work is being done

on the use of permanent magnet focussing for the traveling-wave tubes. The permanent magnet utilized is much lighter in weight than the equivalent solenoid and requires no power supply. This will eliminate two of the objections or limitations of the use of traveling-wave tubes.

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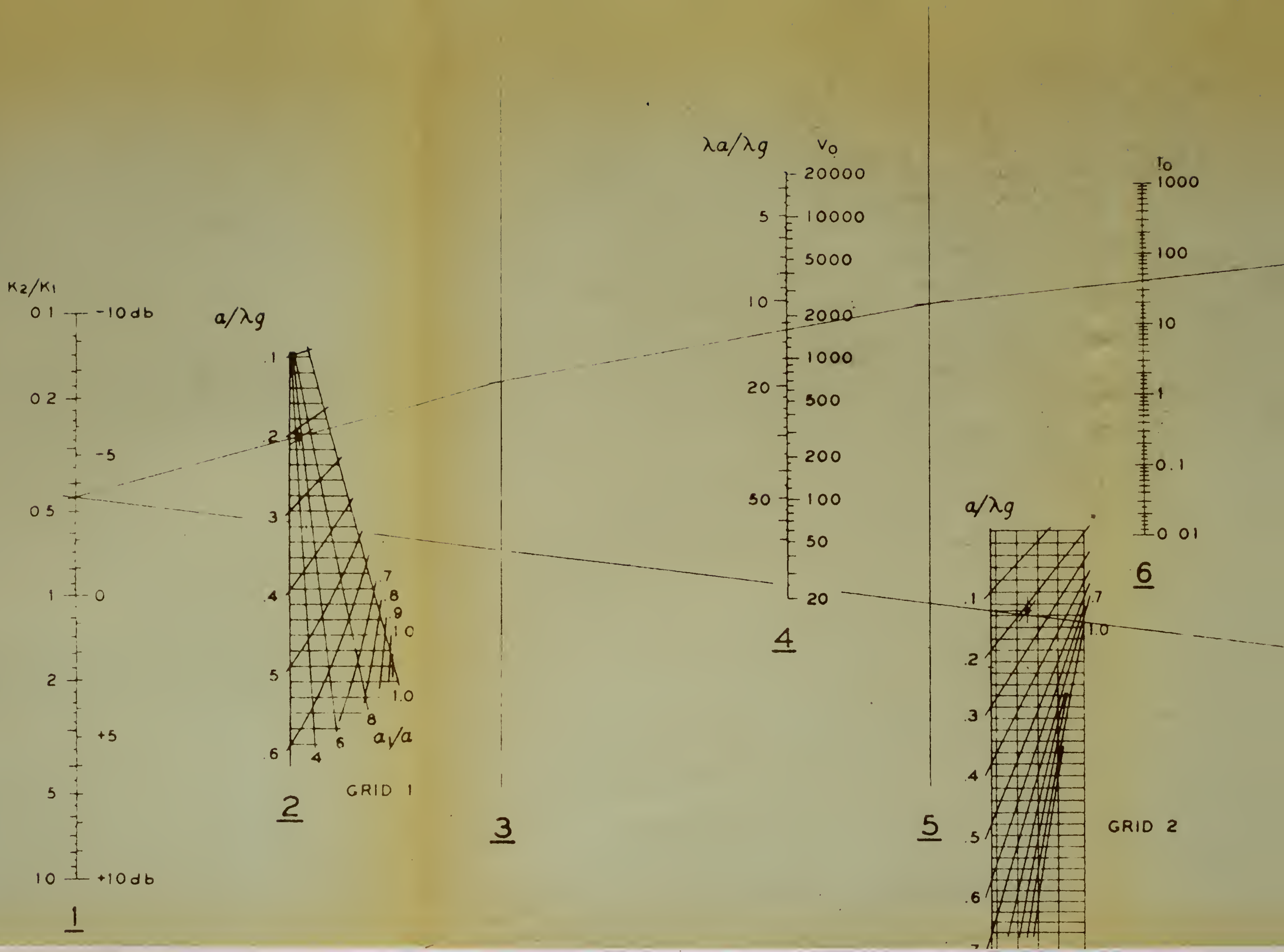

K2/K1
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+5
+10db
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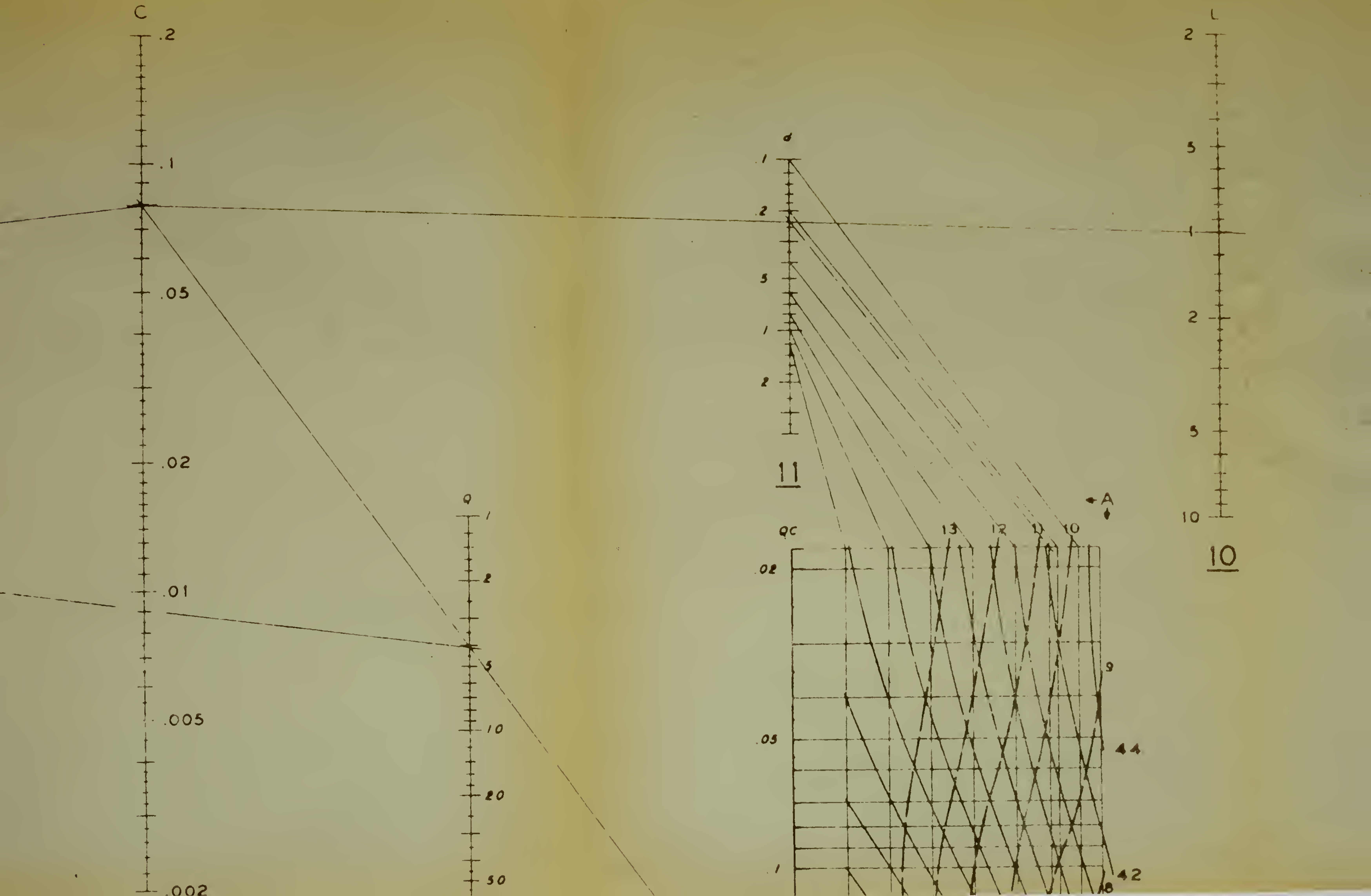
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